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Challenges in 3D Geocellular Modelling of Complexly Faulted - Stacked Reservoirs: Case Study from Existing and Potential Waterflood Areas in Sirikit Field, Onshore Thailand

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Abstract

Central Faulted Region (CFR), East Flank Region (EFR), and Greater Sirikit East (GSE) are the main production areas in the PTTEP S1 Consession, part of Sirikit Field, the biggest onshore oil field in Thailand. The Lan Krabu Formation is the biggest contributor for hydrocarbon production, defined as a thick fluvio-lacustrine deltaic sequence consisting of thin alternations of mouthbar deposits, channels and Chum Saeng lacustrine claystone.

The CFR, EFR and GSE regions are structurally complex, each of which is separated by west dipping, basement rooted main fault. The secondary faults are east dipping antithetic and west dipping synthetic faults which run almost parallel to the main fault. For modelling purposes, detail geological correlation across CFR, EFR and GSE has been established. The correlation utilizes the sequence stratigraphy concept by correlating the flooding surface of the fifth order sequence. The shale interval associated with fifth order flooding surface may inhibit vertical pressure communication or vertical oil movement during production time frame.

Given the highly heterogeneous reservoirs in fluvio deltaic environment together with complex faulting system, it is very challenging to build a geological model that represents the detailed geological features of these areas. Selecting the 3D modelling tools is essensial to generate a model with complicated geological features, in a way that reservoir simulation can be performed in an efficient manner.

This paper will share challenges prior to and during construction of the 3D geocellular model, as well as various modelling approaches that have been generated with multi-scenarios and multi-realizations tasks. It also demonstrates how pixel, object and multi-points statistics (MPS) based approaches in facies modelling along with the application of continuous and discrete N/G provide alternative input for the reservoir modelling. The result of this study will be used for flow performance evaluation and further dynamic modelling.

Introduction

Sirikit Field is located in Phitsanulok Basin, Central Plain, onshore Thailand, approximately 400 km north of Bangkok (Figure 1). The Field is the country's largerst onshore oil field located in the S1 concession, currently operated and wholly owned by PTT Exploration and Production. The Field was discovered in 1981 by LKU-A01 well drilled by TSEP (Thai Shell Exploration and Production).

In effort to increase the oil recovery, Waterflood has been implemented within the Sirikit Area. The East Flank Region was the first region to be waterflooded starting in 1995. The EFR was selected for a waterflood candidate based on the fact that it had the least amount of faulting among the regions. Water injection in Central Faulted Region just started end of 2010. The Greater Sirikit East is a relatively new area, discovered in 2006, and it is still producing under primary recovery.

More recently, series of reservoir modellings and simulations were initiated to investigate sweept efficiency and to optimize the recovery of the current waterflooding areas as well as to investigate the opportunity for waterflooding and infill wells in the potential areas. Figure 7 illustrates the 3D modelling approach that has been conducted in these regions. In a complexly faulted – stacked reservoir enviroment, challenges are faced by both geomodellers and simulation engineers.

The main purpose of this study was to develop a method by which the above challenges are captured; hence, reservoir character and condition can be understood and properly modeled.

Geological Setting and Reservoir Characterization

The oil fields in Sirikit Area are situated within the Phitsanulok Basin. The basin is a major Oligocene extensional structure overlying Mesozoic basement and is the largest of the string of Tertiary intracratonic extensional basins of onshore Thailand. Their Formation is related to the relative movement of continental blocks which presently form the Malayan peninsula and Indochina[5]. The rift basins occur in a roughly N-S oriented zone which coincides with the suture zone of the western Shan-Tai Block and the Indosinian Block which were joined in a continent to continent collision in the Late Triassic during the Indosinian Orogeny.

The Sirikit Field is structurally, sedimentologically and stratigraphically very complex. It is contained in the fluvio-lacustrine sediments of the Lan Krabu Formation. This was deposited early in the Miocene, when a deltaic system prograding from the north was outputting sediments in a shallow lake, forming thin successions of clastic sequences intercalated with the transgressive lacustrine shale of the Chum Saeng Formation (Figure 3). This field is located in central part of the Phitsanulok Basin. The basin has had a complex multiphase structural history - initially extensional, controlling sedimentary accumulation, and then trans-pressional, initiating strike slip structures - which resulted in complex fault patterns and intricate reservoir compartments[5].

Structure

The structural framework of the Sirikit Area is mostly composed of NNE-SSW and NNW-SSE trending basement rooted faults. Most of these faults were created in the first tectonic phase (extensional) and controlled subsequent sediment deposition[1]. These faults have subdivided the Sirikit Area into the following regions: Sirikit Main (CFR and EFR), Thap Raet, Sirikit West (Nong Makham), Sirikit East, Nong Jig and Greater Sirikit East (Figure 1).

The main structure in the Sirikit Main and Greater Sirikit East is a half graben tilted towards the east (Figure 2) that sits on a local basement high. In the Sirikit Main, the K and L reservoirs in the Lan Krabu Formation are densely faulted with extensional faults striking NNW-SSE and dipping predominantly west. Some east dipping compensation faults tend to form and link with the major west dipping faults creating complex compartments. In the Greater Sirikit East, the K and L reservoirs are relatively less faulted than those in Sirikit Main from the seismic data. Faults dipping to the West are observed mostly in the southern part of the field. However, differences in fluid contacts and pressure regimes within a short distance in some blocks may indicate more complex structure than it is currently mapped.

Stratigraphy

The Tertiary sediment fill of the Phitsanulok Basin consists of 3 major subdivisions: Oligocene alluvial fan and alluvial plain deposits, early to mid-Miocene lacustrine and alluvial plain deposits and late Miocene alluvial plain and alluvial fan deposits as shown in Figure 3. The sediments of the first two subdivisions were deposited during the first phase of the formation of the basin (extensional). Initially the clastic sediments of the Sarabop Formation were deposited and then, due to an increase in the subsidence rate, the depositional environment changed to open lacustrine (Lake Phitsanulok) and alluvial plain leading to the deposition of the fluvio-deltaic Lan Krabu and the open lacustrine Chum Saeng Formations in the central part of the basin[5].

In the Sirikit Area, the main contributor for the production is the Lan Krabu Formation. The formation is divided into 4 reservoirs from top to bottom: D, K, L and M. The Lan Krabu reservoirs were mostly deposited during the initial opening phase of the Phitsanulok Basin in the Lower Miocene. Syndepositional faulting is indicated by sedimentary growth along major faults. The reservoirs consist of a set of prograding deltaic sequences that interfingered with the Chum Saeng lacustrine shale deposited during major transgressive events. This has resulted in thin but laterally extensive sand cycles that restrict the vertical communication in the Lan Krabu Formation D, K, L and M reservoirs.

D and M reservoirs which represent the first and last progradation of the Lan Krabu Formation are relatively thin and their distibutions are restricted to the northen part of the Sirikit Area. The 3D Modelling project focuses on the two major contributing sequences, the K and L reservoirs.

The K and L reservoirs consist of fluvio-deltaic sediment sequences that prograded into a shallow fresh-water lake early in the Miocene. Each reservoir divided into 4 sub-reservoirs K1-K4 and L1-L4 that have been identified as coarsening upward sedimentary cycles. The lacustrine shale present at the base (Lower Intermediate Shale), the middle (Upper Intermediate Shale) and the top (Main Seal) of the Lan Krabu Formation correspond to major transgressive surfaces (maximum flooding surfaces). These shale intervals are good seals that are correlatable field-wide and compartmentalize the K and L reservoirs vertically. Table 1 below shows the hierarchical description of the K and L reservoirs and ages for the Sirikit Area. The K3 and L3 intervals show the most proximal depositional environments.

Age	Reservoir	Sub reservoir	Parasequence Sets	Depositional environment
Middle Miocene	Main Seal **(MS)** Chum Saeng			Open lacustrine
	LKU-K	K1	K1, K1.1, K1.2	Lower deltaic
Lower Miocene		K2	K2, K2.1, K2.2, K2.3, K2.4, K2.5	Lower deltaic
		K3	K3, K3.1, K3.2, K3.3	Floodplain
		K4	K4, K4.1, K4.2, K4.3, K4.4	Lower deltaic
	Upper Intermediate Seal **(UIS)** Chum Saeng			Open lacustrine
	LKU-L	L1	L1, L1.1, L1.2	Lower deltaic
		L2	L2, L2.1, L2.1, L2.2, L2.3	Lower deltaic
		L3	L3, L3.1, L3.2, L3.3	Floodplain
		L4	L4, L4.1, L4.2	Lower deltaic
	Lower Intermediate Seal **(LIS)** Chum Saeng			Open lacustrine

Table 1: Hierarchical Subdivision of the Lan Krabu K and L Reservoirs in Sirikit Main and GSE

Correlation

Correlation has been established by combining standard wireline logs with seismic stratigraphy, where applicable. The seismic horizons used are the top of the Main Seal, the top of the LKU-K and the top of LKU-L as they are the most field wide continuous features that can be used to image the general structure of the reservoir.

The correlation approach follows the principle of chronostratigraphy i.e. time lines represented by flooding surfaces. For the 3D static geological modelling, the correlation is focused on Lan Krabu K and Lan Krabu L reservoirs. The K and L reservoir can be considered as third order stratigraphic sequences that are bounded by maximum flooding surfaces. The K Reservoir is bounded to the top by Main Seal (MS) and to the bottom by Upper Intermediate Seal (UIS). The L reservoir is bounded by UIS at the top and Lower Intermediate Seal at the bottom. This maximum flooding surface shale has been proved as an effective vertical seal for the hydrocarbon accumulation over the Sirikit Field.

The K and L reservoirs were subsequently divided to fourth order sequences or sub reservoirs up to 100-200 m, labeled as K1, K2, K3, K4 and L1, L2, L3, L4. The sub reservoirs consist of multiple coarsening upward parasequence sets and are separated by flooding surfaces that have also been proved as local seal in some parts of the field.

The reservoir correlation is further refined to finer intervals of 30-40 m parasequence sets or fifth order sequence. The correlation framework from the third to fifth order sequences is shown in Figure 4. This refined subdivision is intended to better assess the reservoir connectivity and to maximize the determinism of the model. Each parasequence set is separated by minor flooding surface shale that may inhibit the vertical communication of the reservoir as proven in Greater Sirikit East Area. The correlation at this level of detail is not always strait forward due to less extensive flooding surface, complex faulting system and erosion in some areas. Figure 6 shows the correlation of the stratigraphically representative wells across CFR, EFR and GSE regions.

Facies Interpretation

The facies interpretation was mainly based on the electric log shape and character. However, when the core data is available the facies interpretation from the logs is calibrated using the core (Figure 5). From the core study, Flint et al (1988) has classified the facies in Lan Krabu Formation into 3 types of reservoir facies (S1, S2 and S3), 3 types of claystone facies (C1, C2 and C3) and two types of interbedded sand-claystone or siltstone-claystones facies (Cs and P). The first three sand facies are commonly observed as reservoirs in the fluvio deltaic environment, i.e. mouthbar (S1), channel (S2) and crevasse splays (S3), and can be interpreted from the well log. The interbedded sand/siltstone/claystone facies, most of the time, is not resolved by the log data. When the facies is resolved by log resolution, this facies is included as part of mouthbar facies. The remaining facies is set as background shale for simplicity of the 3D Static Modelling.

Mouthbar deposits occur when a river system outputs sediments in the sea or in a lake. They are typically composed of thin, stacked sands and usually show better reservoir properties at the river mouth. A mouthbar can interfinger with a neighboring mouthbar and typically contains shalier intervals that correspond to river avulsion or to an increase in accommodation space. Mouthbar facies is characterized by a coarsening upward trend on Gamma Ray logs associated with a sharp top. From the core sample, the mouthbar is characterized by thin to medium thick sands (0.5-4m), can be relatively extensive; coarsening upward, porosity ranges from 19 to 22 %. Mouthbar sands are commonly associated with acoustically soft lacustrine shale. In the CFR, EFR and GSE area, this facies is accounted for around 80% of the reservoir facies.

Channel facies can be recognized on the logs from a sharp base associated with a fining upward trend characterized by a bell or sometimes blocky shape on the gamma ray (Figure 5). The channel deposits are mostly point bar sands, relatively thick (1-7m), however some thin sands are interpreted as channel in the cores which may represent the edge of the channel. They are laterally not very extensive as it is rarely possible to correlate them between wells perpendicular to channel orientation with average well spacing between 250 and 500m. This can be a criterion for segregation from mouthbar or crevasse sands which are are expected to be penetrated by several wells. The channel sands are typically cutting through the harder floodplain shale with porosity ranges from 18-25 %.

Crevasse splays are very thin (0.3-1m) and relatively extensive. Crevasse splay sands are difficult to distinguish from mouthbar or channel edge from the log motif only. Their determinations are also based on their association with the channel deposits.

Structural Framework Modelling

The main challenge faced during modelling the Sirikit Area (CFR, EFR and GSE regions) is the structural modelling. The regions are structurally complex, each of which is separated by west dipping, basement rooted main fault. Most of these faults are listric faults. The secondary faults are east dipping antithetic and west dipping synthetic faults. In some cases, the younger faults cut and offset the older faults which further complicate the structure. With the very complex geological nature in Sirikit Field, geomodeller often sacrisfy the 3D modelling construction by oversimplified of the true structure - to leave faults data out, or to modify the faults such as verticalizing the fault planes and splitting the 3D grid into several reservoir zones so that the special-case scenario is avoided[3].

In the classical approach, the pillar-and-node based method is defined using fault traces. One fault trace will truncate on another at a node. The pillars consist of a maximum of 5 nodes, at which the insection node will be shared when one fault surface connects to another fault. In the case of study area, listric faults in conjuction with their antithetics (Figure 8) make this classical method difficult to use. A listric fault is a curved normal fault, concave upward, where the dip of the fault is fairly steep shallow and decreases with depth, often becoming almost horizontal[3]. In this study, a new modelling approach was adopted for the construction of the structural framework and 3D grids. First step is to construct the fault framework using pillar-less approach. Then the fault intersections are cleaned up by utilizing fault tip line, and/ or digitizing fault intersections. Second step is to generate reference horizon modelling from the interpreted (depth converted) horizons which only tied to the well markers (Figure 9a). The final step is to generate the reservoir zones, called nested horizons modelling by utilizing well picks markers and isochore models (Figure 9b). This workflow is known as integrated horizon modelling.

Classical Problem of 3D Grid Construction

As the nature of the fluvio-deltaic depositional environment is already bearing a highly heterogeneous reservoir, compounded with the complex faulting structure, it is very challenging and difficult, in term of geology, geophysics and reservoir engineering, to create a 3D geocellular model that represents detailed geological features in this areas. Although the modelling capacity and tools are commercially available to generate such a complicated geological feature of the reservoir, the model should also be built in the ways that reservoir simulation can be performed in an efficient manner[4].

The key component is the basic structural framework; all subsequent calculations depend on it. With such structural framework and grid requirement, the fault curvature can also be captured in 3D grid construction by the stair-stepping the faults approach. This method is to avoid grid twisting and to minimize grid collapsing that cause hassle in dynamic flow simulation. The grid result is orthogonal (i, j) and vertical (k) and this type of grid is very suitable for simulation purposes. Figure 10 illustrates the different approaches of the 3D geocellular building.

Multi Scenarios Facies Modelling

The other challenge is the spatial distribution of facies and reservoir properties within a heterogenous reservoir. The prediction of facies distribution bears significant uncertainties when only based on well information. Integrating additional constraints such as 3D seismic data and sedimentary concepts can significantly improve the accuracy of reservoir models and help reducing uncertainties on predictions away from wells[6].

Where seismic quality is good, it is often possible to interpret sedimentological features on horizon slices even where the facies bodies are thinner than the seismic resolution. In fact, seismic data quality and resolution are poor at this regions. Only in GSE Region the seismic data can be used to recognize the shale-out line at top of LKU-K and LKU-L (Figure 14).

To overcome this limitation, geomodeller has to define trends to control facies distribution in the 3D geocellular grids. Trends can be defined using one, two and three dimentionals. 1D trend is called vertical proportional curve (VPC). 2D trend is a map trend which can be defined using polygon and reference line constructed from knowledge based approach such as conceptual depositional settings with support from well data. The 3D trend is mostly generated from well data incorporating neighborhood information (x,y,z). In this study case, the 3D trend has been generated to produce facies probability trend in combination with 1D VPC. Figure 12 illustrates the trends that have been applied in the facies modelling workflow.

Several facies modelling scenarios have been proposed and applied in this regions to model the uncertainties. Seven facies models have been produced for CFR-C1 reservoir model from pixel, object and combination between pixel and object based approach (Figure 11 and 13). The multi-point statistics (MPS) has also been investigated to be used in the modelling. It is called multi-point due to utilizing several points in one time analysis of the data. As comparison, the traditional geostatistics uses two point during variogram exercise. To come up with multi point, MPS needs training images (TI) library prior to running process. Figure 14 illustrates the MPS workflow[7].

Reservoir Properties Distribution

This paper would also emphasis on the net-to-gross (NTG) modelling that is crucial when the 3D grid cells are relativelly coarse. Figure 16 illustrates the comparison between the well logs and the grid scales. There are two choices in modelling the NTG; discrete and continuous. The information for the discrete treatment of the NTG is already exists in the log scale facies modelling. Simply, the background shale is assigned NTG = 0, and mouthbar, channel and crevasse are all assigned NTG = 1. The critical assumption is that the criteria for facies definition encompass the criteria for net sand definition so that it can be used to define NTG.

In the continuous approach, the fine grid static model blocks are assigned averaged NTG values from the log scale net flag information (or continuous NTG log). Hence NTG values vary from 0 to 1. With this method of NTG modelling, the facies distribution may or may not be modeled. If the facies distribution is modelled, it can be used to control the NTG at the wells and the distribution between the wells. If the facies is not modelled the NTG at the wells is derived solely from the log scale net flag (or continuous NTG log) information, although it's distribution between the wells can be controlled by porosity.

The proposed method is to constraint the 3D reservoir properties model with the facies model, which porosity, permeability and NTG are modelled together with colocated cokrigging approach. This technique makes full use of facies tagging interpretation at the well and captures fine scaled reservoir properties heterogeneities observed at the well.

Conclusions

The major challenge in 3D reservoir modelling is to bring all data, each at its own scale of information, into a single numerical model. The CFR, EFR, and GSE Regions can be modeled with a good knowledge and the proper 3D modelling software. New approach of structural framework building using a robust 3D modelling tools has made it possible to model complex structure and reduced the cycle time of constructing the framework, thus it allows more in-depth investigation of reservoir properties. Seven modelling scenarios have been applied to distribute the reservoir facies and properties as well as capturing the uncertainties. There are two approaches used in NTG modelling, discrete and continuous; where the 3D grid cells are relativelly coarse, it is suggested to proceed with the continuous approach. Structural framework and reservoir properties distributions that corectly represent the subsurface interpretation are required for flow performance evaluation and further dynamic modelling.

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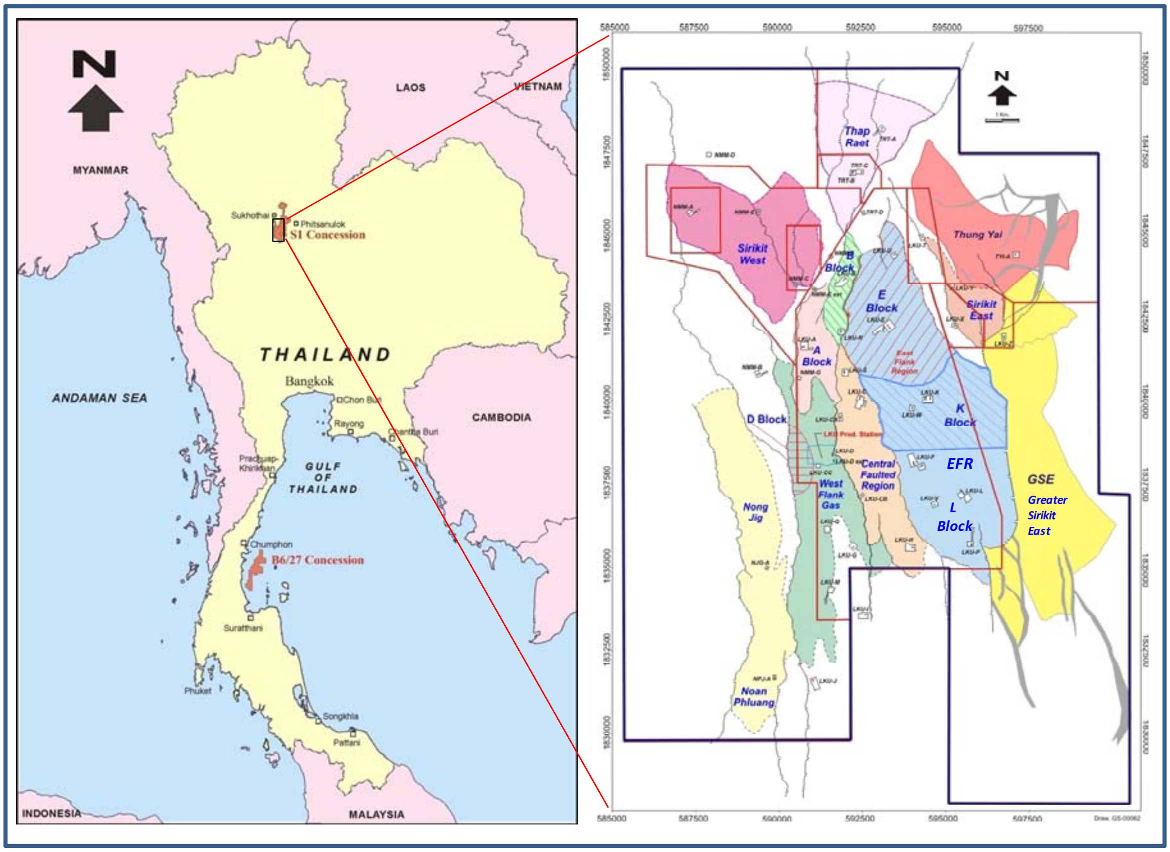

Figure 1: Location and Block Definition of the Sirikit Field

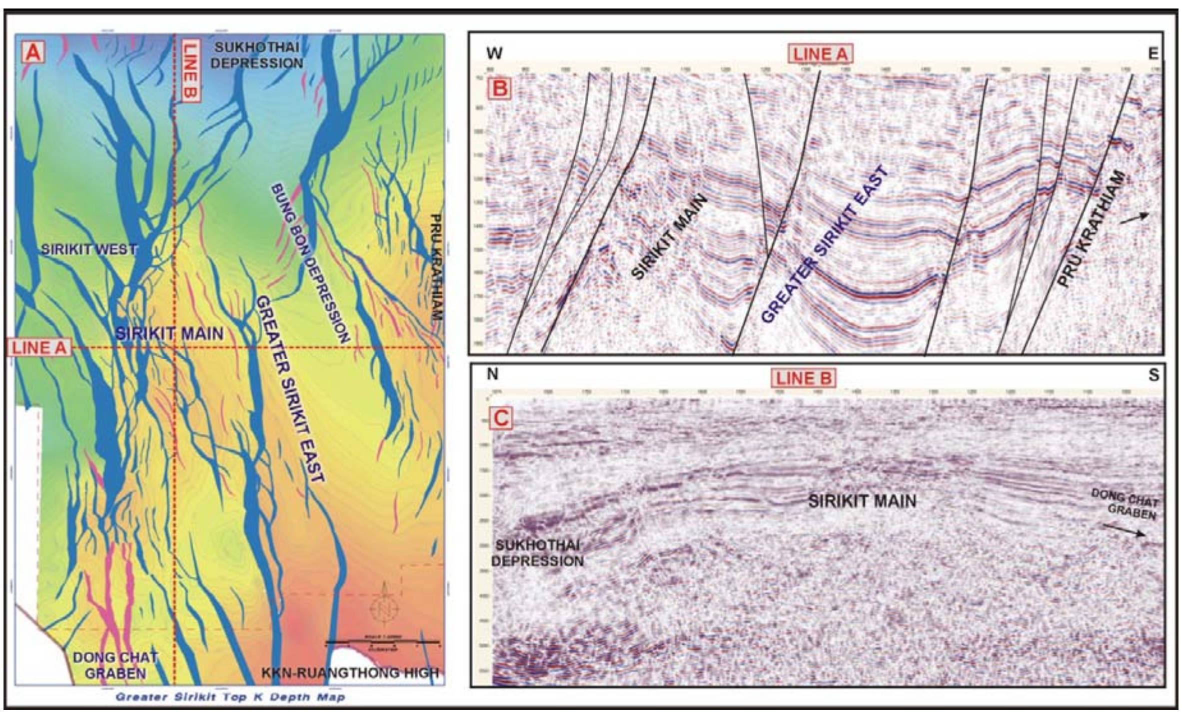

Figure 2: Sirikit Field Structural Setting. (A). Regional Top Lan Krabu K Structural Depth Map showing the predominantly west dipping basement rooted faults (blue) and east dipping compensation faults. (B). E-W seismic section showing the series of east dipping tilted half graben. (C). N-S seismic section

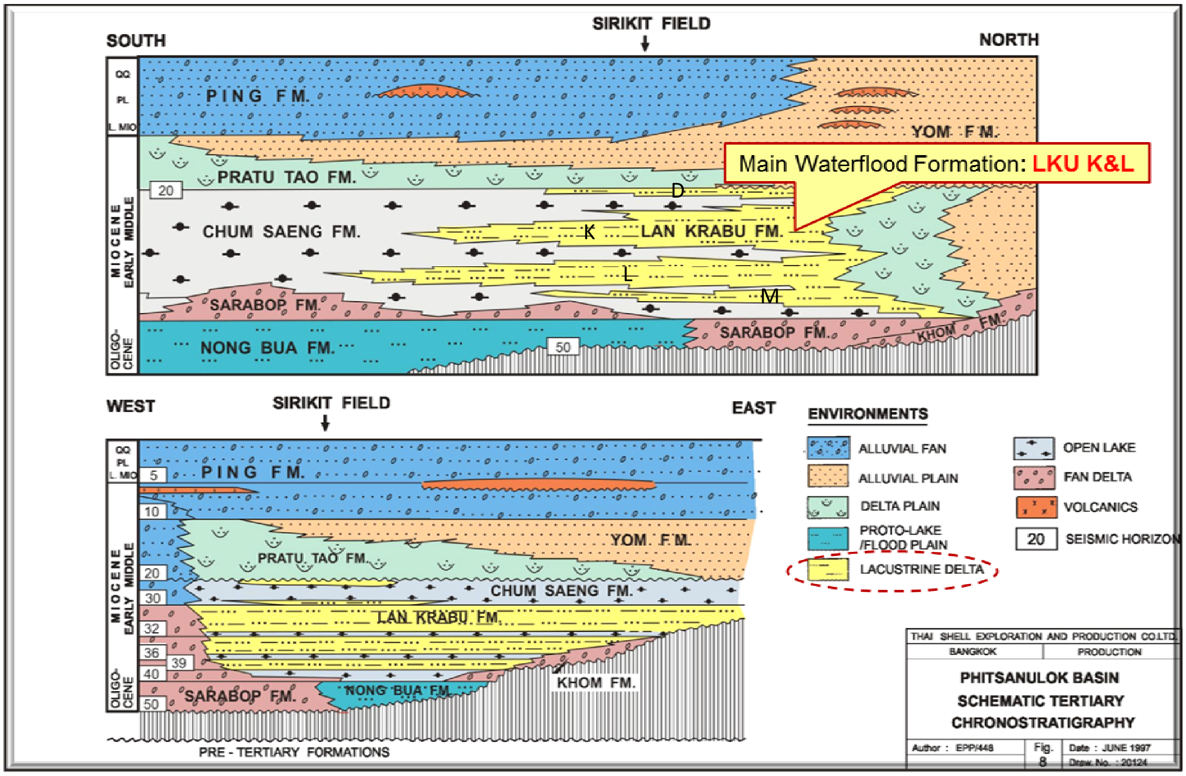

Figure 3: General Stratigraphy of the Phitsanulok Basin

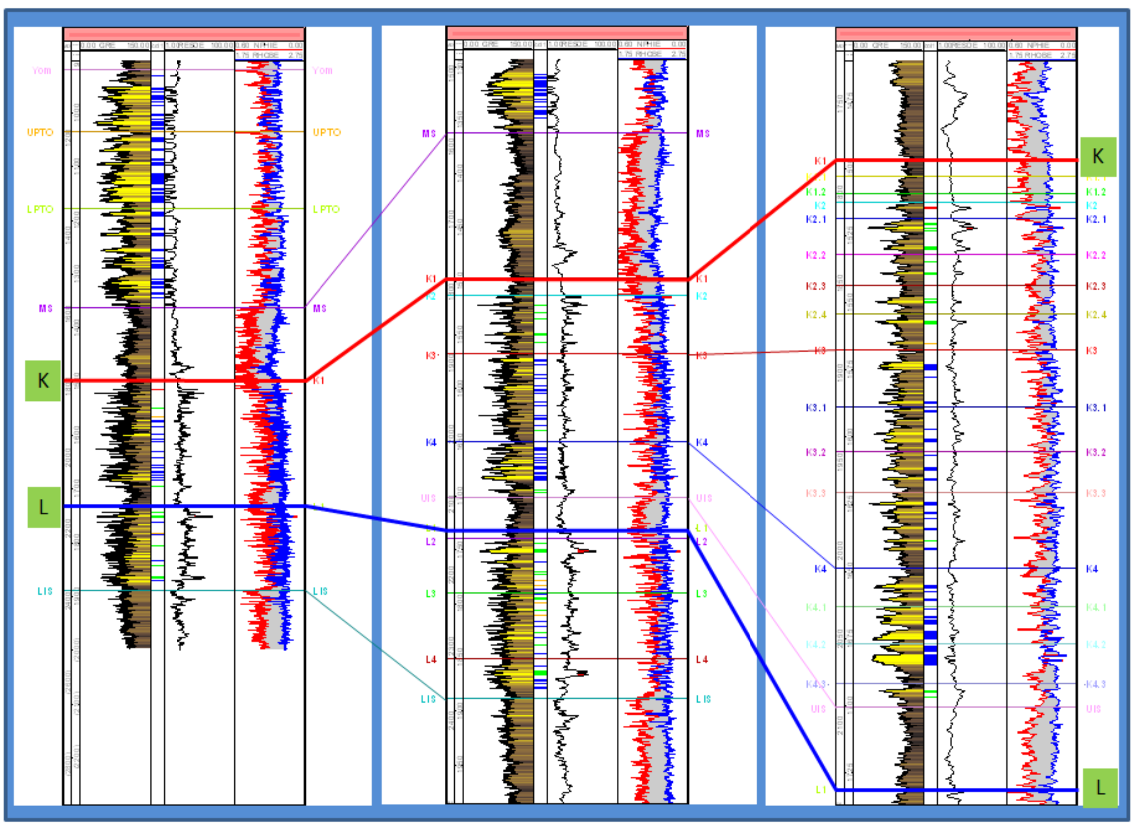

Figure 4: Correlation Framework of the Sirikit Area (CFR, EFR and GSE)

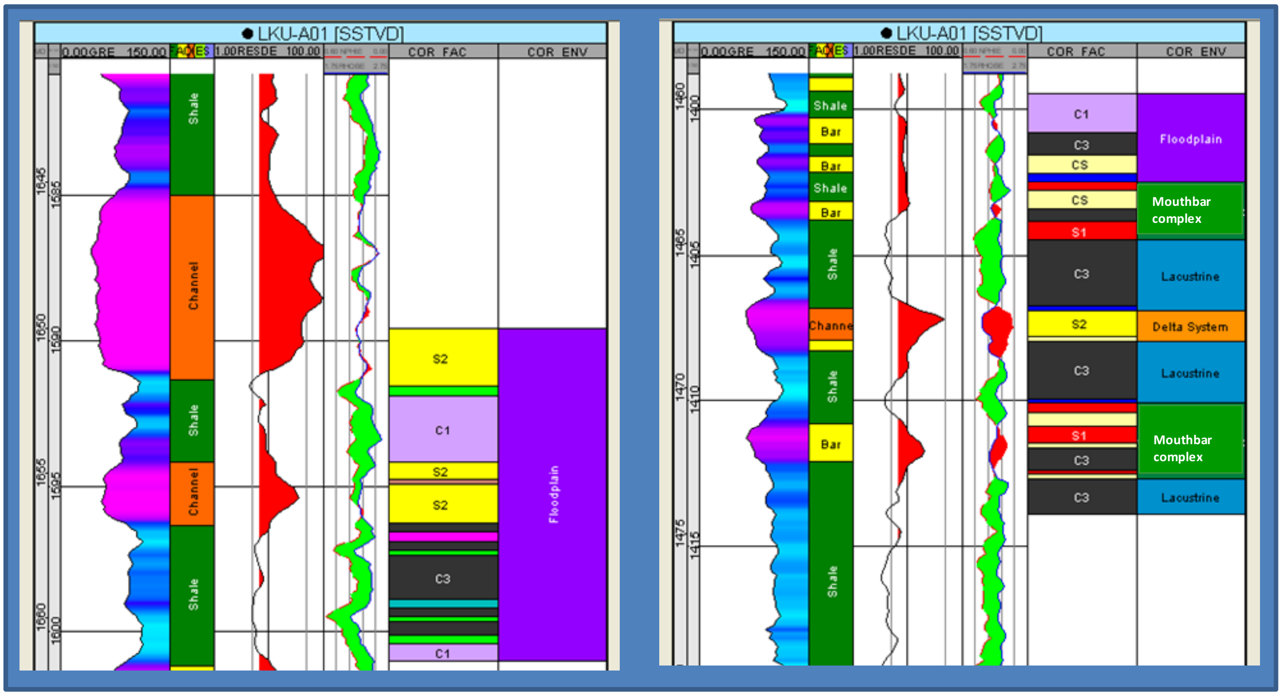

Figure 5: Electric log facies interpretation calibrated to the core data

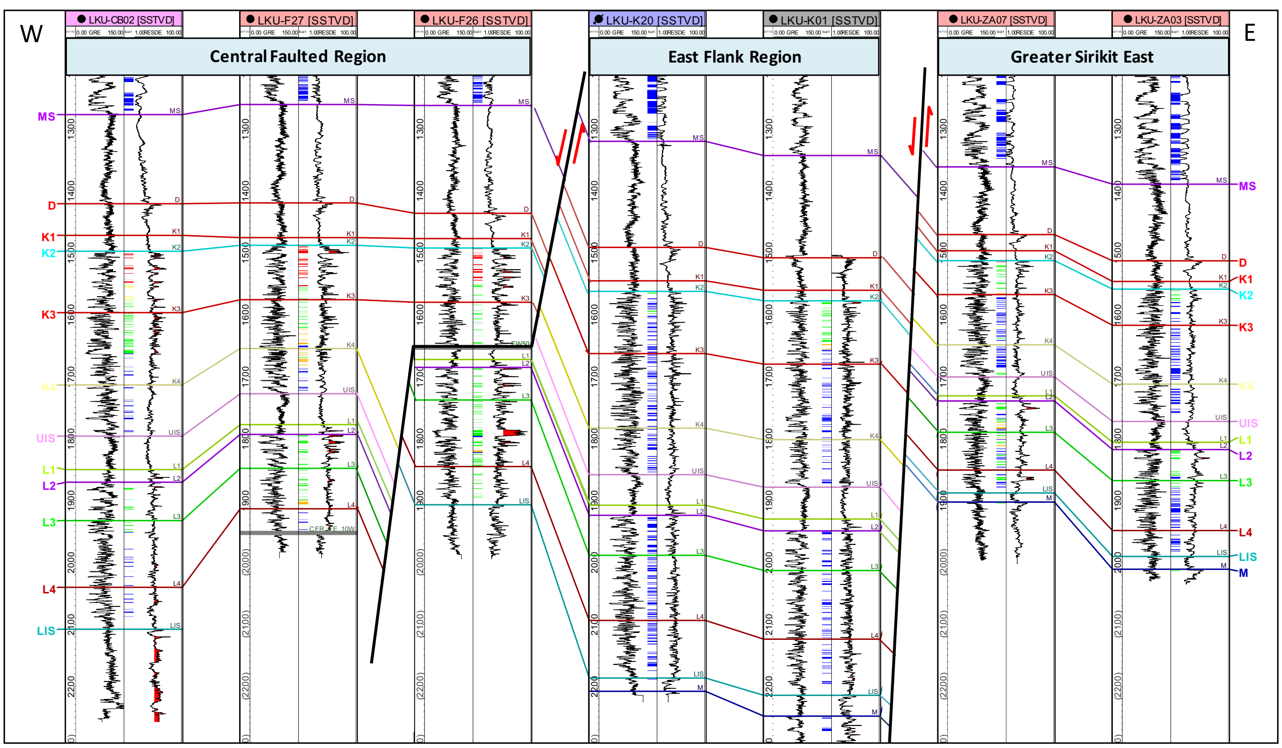

Figure 6: E-W Structural Correlation across Central Faulted Region, East Flank Region and Greater Sirikit East

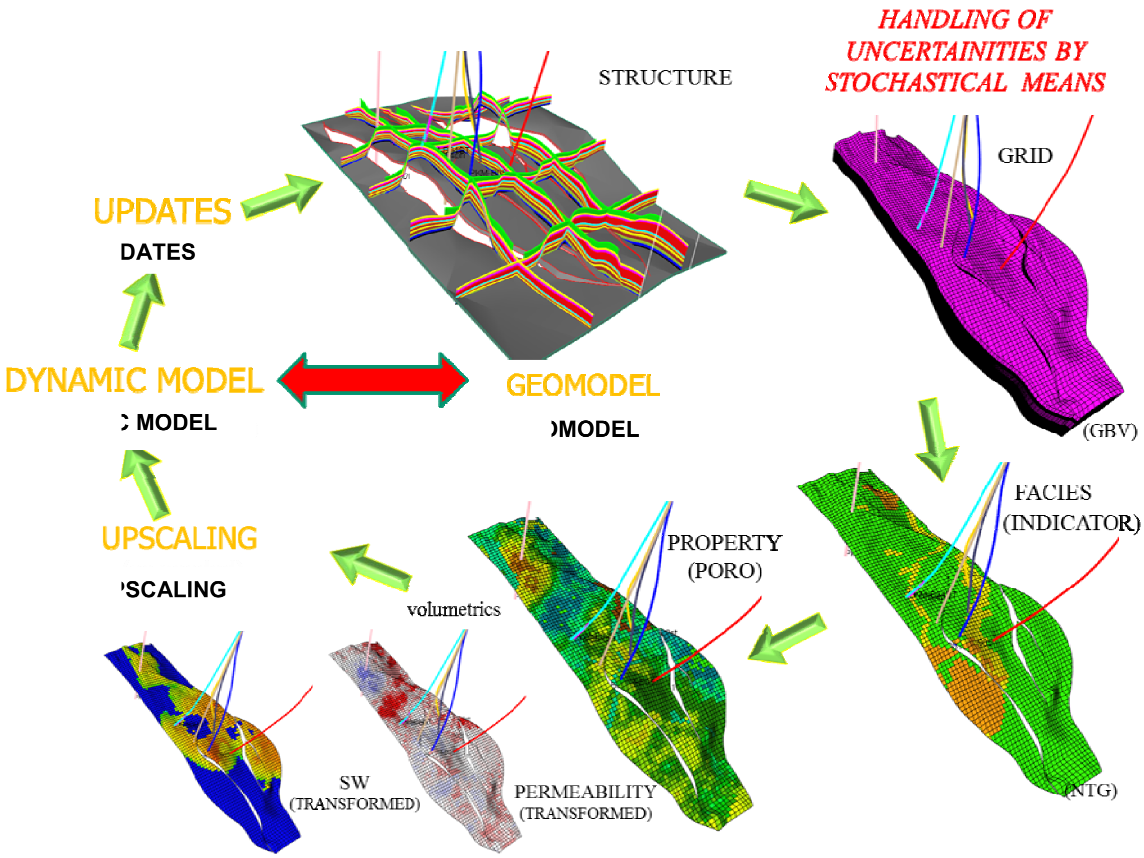

Figure 7: 3D Modelling approach in CFR, EFR and GSE Regions. Itteration process can be done on each realization or scenario, i.e. 3D grid construction, facies modelling, property modelling, etc. Including upscalling model for dynamic simulation

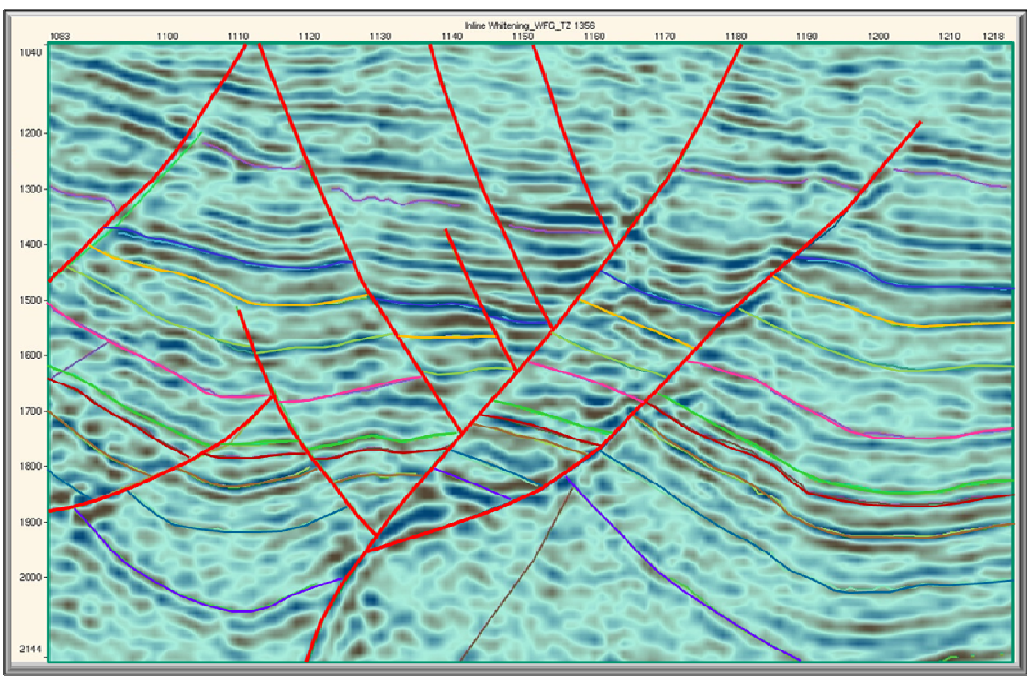

Figure 8: Faults and horizons interpretation of Listric faults and Y-intersection to be modelled in CFR and EFR Regions. Low angle angle faults and low angle intersection also pose problem for pillar-based methods. It can distort the shape of one or both faults

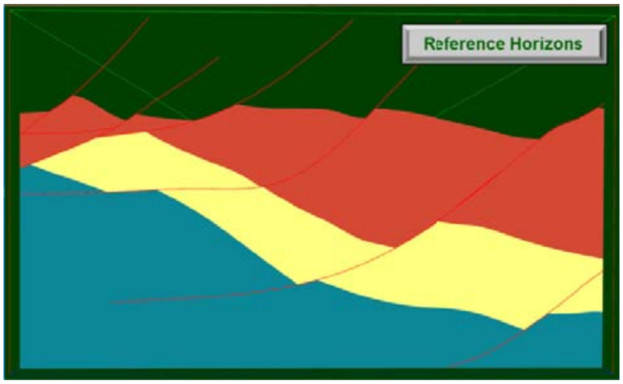

Figure 9a: Example of Reference horizons in CFR during Horizon modelling process by utilizing fault model, depth horizon interpretation and well pick markers

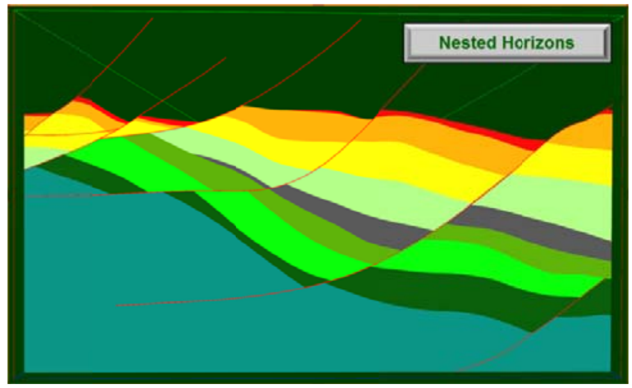

Figure 9b: Example of Nested horizons in CFR constructing by utilizing Reference horizons, well pick markers and isochore models

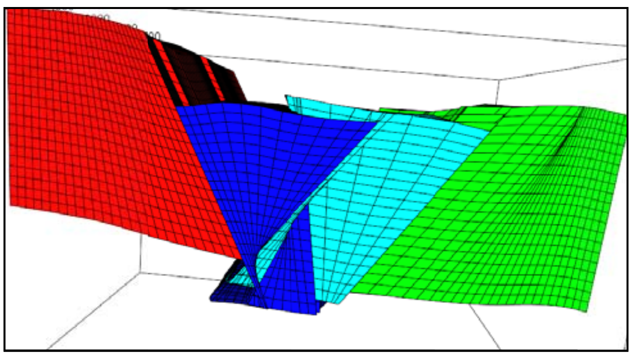

Figure 10a: Faulted 3D geocellular construction by applying all fault pillars causing twisting cells at the fault intersections

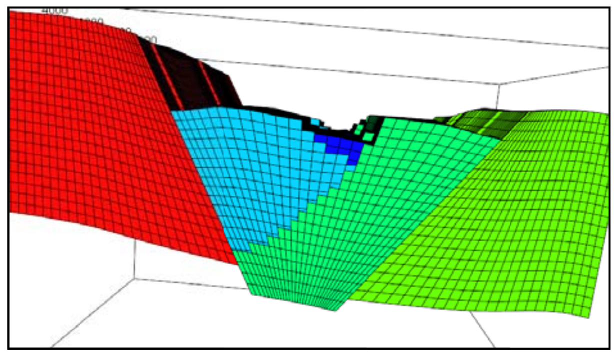

Figure 10b: Faulted 3D geocellular constructon by applying partly fault pillars and stair-stepping causing distorting cells

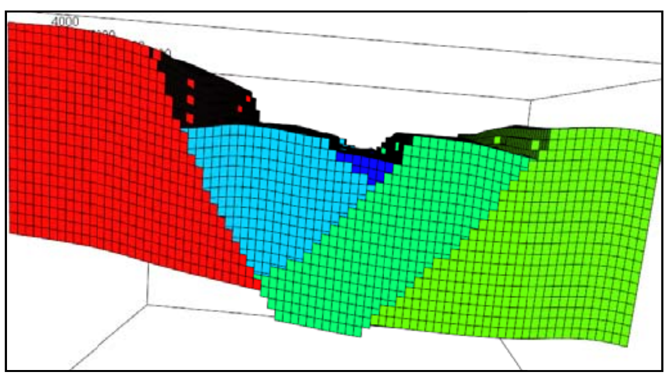

Figure 10c: Faulted 3D geocellular construction by applying all fault stair-stepping can generate perfect orthogonal shape that most preferable in simulation

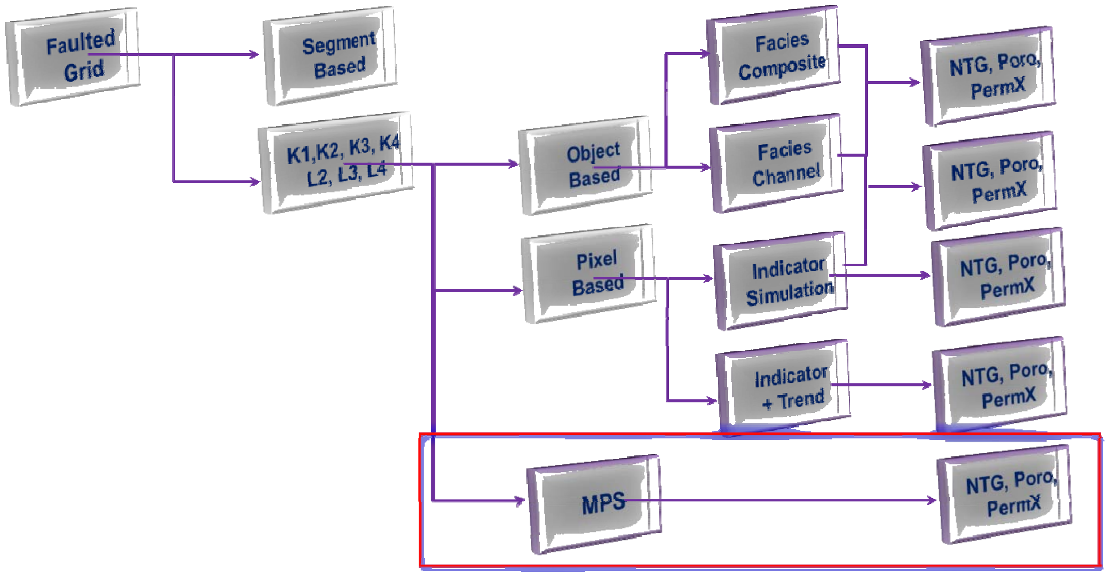

Figure 11: 3D geocellular modelling tree to illustrate the discrete facies modelling consist of pixel, object and multi-point statistic (MPS) approach to constraint reservoir properties such as continuous NTG, porosity and permeability

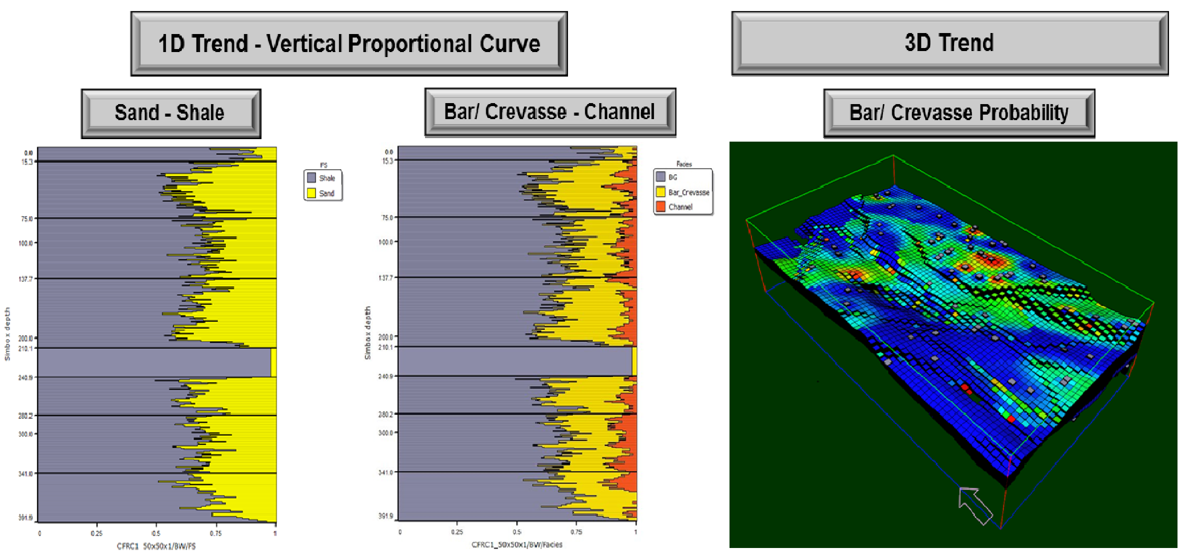

Figure 12: One and three dimentional trends have been utilized as soft control in populating sand-shale pixel or bar/ crevasse and channel object in 3D geocellular models, hence a combination of both trends also been applied

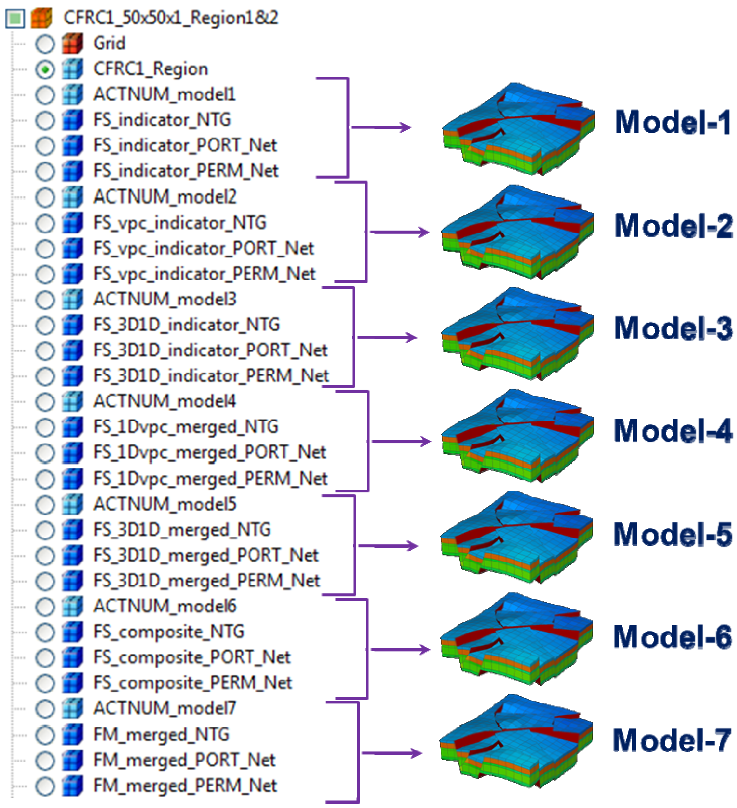

Figure 13: An example of facies modelling in CFR-C1. Seven scenarios have been generated using pixel, object and combination pixel and object based method to produce seven of facies models

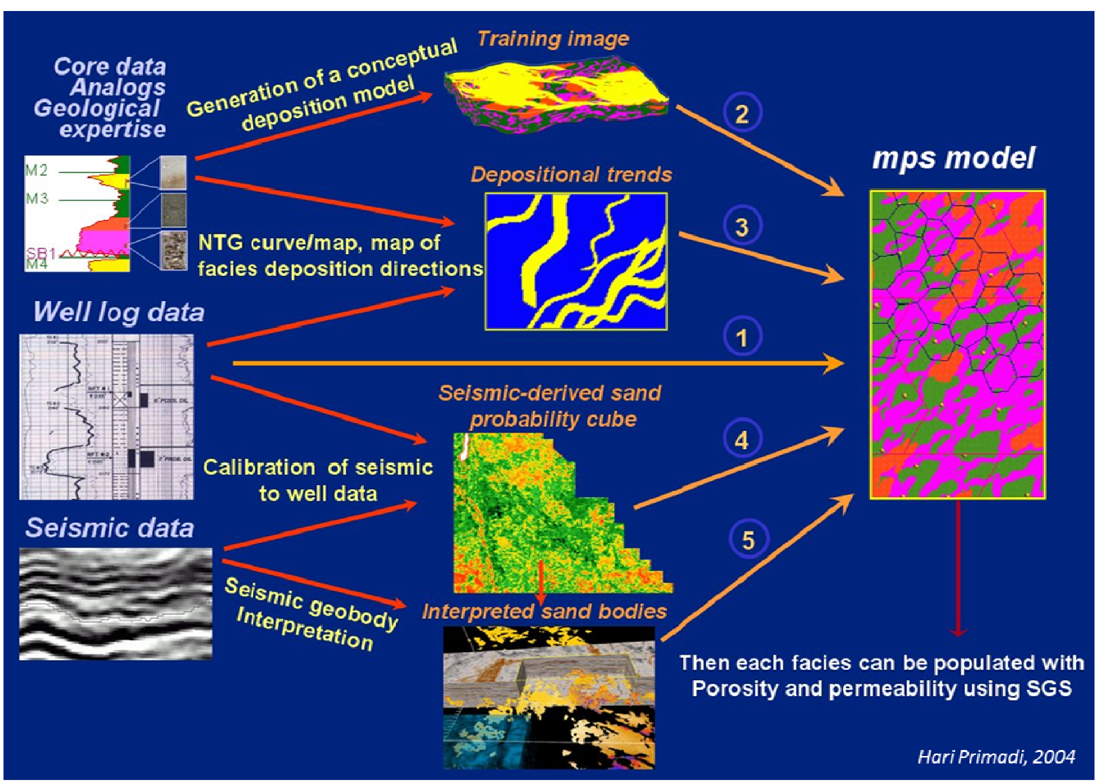

Figure 14: Multi-point statistics (MPS) workflow also has been investigated to be applied in this area. Several Training images (TI) have been produced prior to running MPS modelling

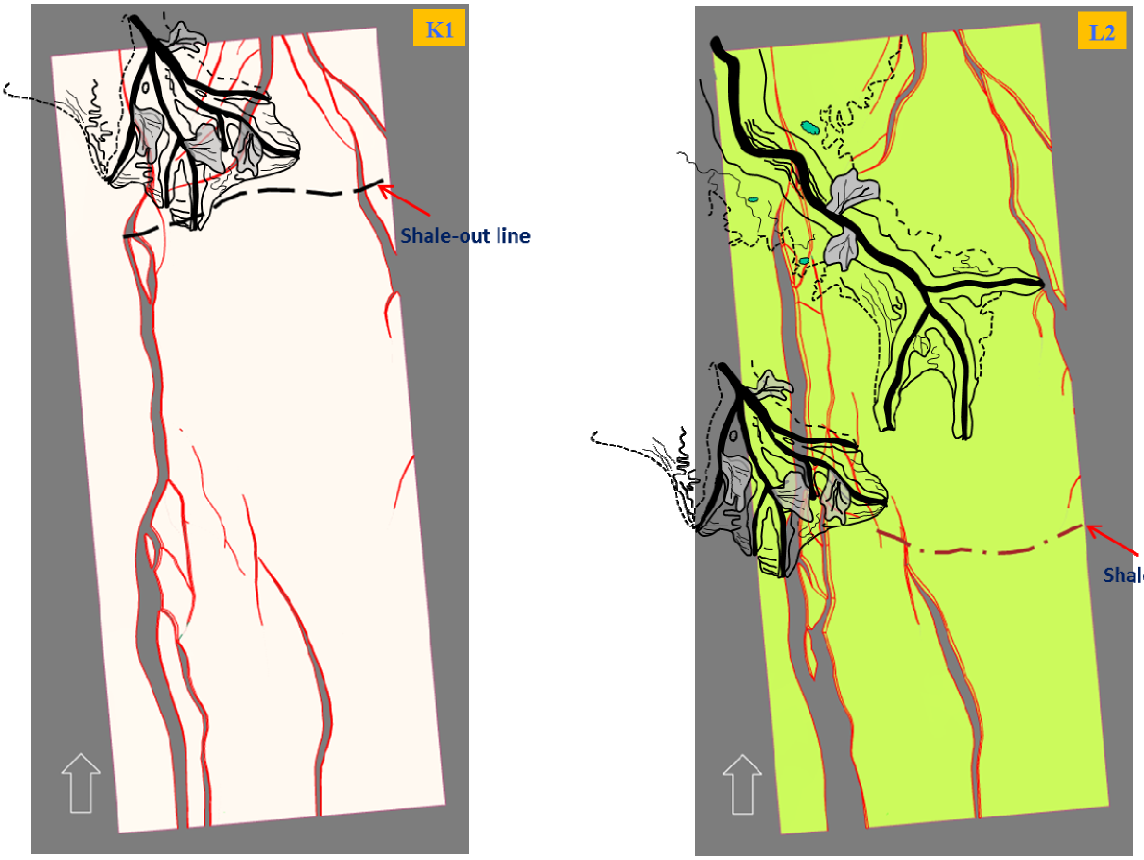

Figure 15: Two examples of training image (TI) construction in GSE Region prior to run MPS workflow. Combination of conceptual geologic models and qualitative geophysical input (i.e. shale-out line)

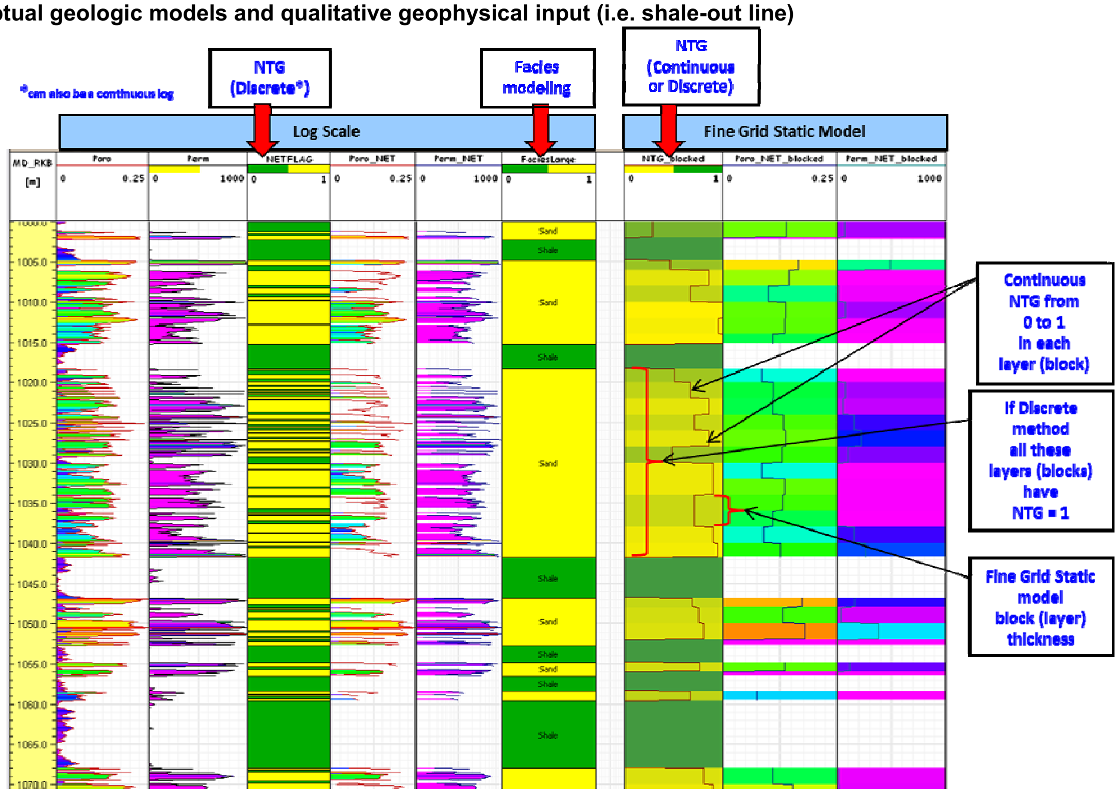

Figure 16: Composite logs to compare between well log and fine grid scales. This illustrates the heterogeneity resampled into grid resolution, emphasis on NTG track